Microstructure of particle-strengthened materials. A study on Ni-base superalloys and Al-Li base alloys

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SUMMARY

The theory of order hardening is used to calculate the contribution to the shear stress of a superlattice dislocation in a binary AL-Li alloy with 2.9 volume percent of small $\delta'(L1_2, Al_3Li)$ precipitates (R = 7.2 nm). The measured increase of yield stress is in reasonable agreement with the calculated value. From the separation of a superlattice dislocation the APB energy of Al_3Li is calculated to be 139 mJ/m^2. Orowan looping occurs around larger δ' precipitates with radius 68 nm (4.5 volume percent). In commercial Al-Li base alloys the effect of Zr, Cu and Mg has been described and composite precipitates (Zr-rich core, δ' shell) are analyzed by EDS.

The mean jump distance of moving dislocations in binary Al-Li alloys is measured by NMR. At small strains δ' precipitates are shearable during deformation resulting in a large jump distance whereas the interparticle spacing of larger non-shearable precipitates sets an upper limit for the slip distance. As deformation goes on the slip distance is determined by the spacing between statistically stored dislocations. Also the mean activated length of dislocations is measured by strain rate change experiments. In all alloy systems the mean jump distance (L) exceeds the activated length (λ) because experimentally L is controlled by relatively hard obstacles (precipitates and forest dislocations) whereas λ is determined mainly by forest dislocations.

In Ni base superalloys about 50% of the volume is occupied by $\gamma'(L1_2, Ni_3(Al,Ti))$ precipitates arranged as a stacking of cubic blocs (edge length about 200 nm). The dissociation mechanisms of unit dislocations in $L1_2$ ordered material are applied to alloys with $L1_2$ ordered precipitates in an f.c.c. matrix. If the matrix stacking-fault energy is high the matrix will be deformed by unit dislocations which dissociate at the interfaces of precipitates thereby avoiding formation of APB's. If the matrix stacking-fault energy is low the matrix will be deformed by coupled Shockley-partial-dislocations and precipitates can be sheared without interfacial constrictions and without inducing CSF's due to dipole displacements.

The LCF deformation behaviour of the superalloy PM Astroloy is summarized in a deformation map. At low temperature and high strain rate (about 400°C, $10^{-2}s^{-1}$) precipitates are sheared by superlattice dislocations. Shearing of precipitates by partial dislocations and glide-climb of dislocations is observed at higher temperature and lower strain rate (about 700°C, $2 \cdot 10^{-6}s^{-1}$).

The low temperature tensile strength of the superalloy MA 6000 is approximated by the shear stress of a superlattice dislocation by incorporating the detachment stress of yttrium-oxide particles. After about 2% creep or tensile deformation near 760°C the dominant feature of the microstructure is the presence of stacking faults in γ' precipitates. By TEM evidence has been found for dissociation of a unit dislocation at the interface: $a/2[\bar{1}0\bar{1}] \rightarrow a/3[\bar{2}1\bar{1}] + a/6[1\bar{2}\bar{1}]$. The matrix is deformed by $a/2[\bar{1}0\bar{1}]$ whereas the precipitate is faulted by $a/3[\bar{2}1\bar{1}]$. At the interface an $a/6[1\bar{2}\bar{1}]$ dislocation loop is left behind. As deformation proceeds, faults extend into the matrix and form microtwins which reach a considerable density at fracture in tension. In addition, this analysis is confirmed by *in situ* TEM observations.

After fracture in creep at 538 MPa (at about 760°C) the surface of a MA 6000 creep specimen contains cavities associated with fine grains which are found within the coarse elongated grains due to recrystallization. In HTLCF experiments ($\dot{\varepsilon}=5 \cdot 10^{-5}$ s^{-1}) at a low stress level in the intermediate temperature range (760-850°C) these fine grains are a site of crack initiation. The outer surface of a fine grain consists of agglomerated γ' precipitates. It seems reasonable to assume that crack initiation occurs by the formation of cavities as observed after creep fracture. At a high stress level at intermediate temperatures fracture initiates at the surface of a specimen. As a result of the coarse grains in MA 6000 the transition from trans- towards intergranular crack initiation is shifted towards high temperatures. Softening during fatigue has been found clearly at 950°C which is near the maximum in fracture strain.

After fatigue at 760°C the dominant feature of the microstructure is the deformation by stacking faults, as observed af-

ter creep. However after fatigue at 850°C TEM micrographs show only dislocations obstructed at interfaces of precipitates and matrix. At 950°C and 1050°C instability of the microstructure limits the fatigue resistance of MA 6000. Coalescence of precipitates leads to a coarse precipitate structure with a network of misfit-dislocations formed on the interfaces of precipitates and matrix.